REMARKS

Attached hereto is a marked-up version of the changes made to the claims by the current Amendment. The attached pages is captioned **Versions with Markings to Show Changes Made.**

Claims 1-27 are pending.

The Examiner indicated that the listing of references in the specification should be submitted for consideration. Accordingly, Applicants submit herewith an Information Disclosure Statement with copies of the references.

Applicants submit herewith a substitute specification that corrects minor errors and adds headings in accordance with preferred U.S. patent practice. It is respectfully submitted that no new matter has been added.

Claims 9-15 and 17-27 stand objected to because of informalities. Accordingly, Applicants have amended claims 9-15 and 17-27 to address the concerns of the Examiner and therefore, it is respectfully requested that the objection be withdrawn.

Claims 8-27 stand objected to under 35 U.S.C. § 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter that Applicant regards as the invention. With regard to claims 8 and 16, the Examiner states that the phrase "an ohmic contact to a semiconductor" is unclear as to whether it recites any specific structure or device. Accordingly, Applicants have amended claims 8 and 16 to address the concern of the Examiner. It is respectfully submitted that all claims now fully comply with 35 U.S.C. § 112 and therefore, it is respectfully requested that the rejection be withdrawn.

Claims 8, 9, 16, 19 and 23 stand rejected under 35 U.S.C. § 102(b) as being anticipated by Hartnagel et al. (U.S. Patent No. 4,119,993).

Claims 8-13 and 15-27 stand rejected under 35 U.S.C. § 102(a) as being anticipated by Nitta (U.S. Patent No. 5,798,537).

Claims 8-26 stand rejected under 35 U.S.C. § 102(e) as being anticipated by Nakamura et al. (U.S. Patent No. 5,563,422).

These rejections are respectfully traversed and reconsideration is respectfully requested. With regard to the rejection of the claims in view of Hartnagel et al., it is respectfully submitted that the material of the ohmic contact formed based upon the disclosure of Hartnagel et al. is metal (see column 1, line 52-column 2, line 2), which does not include a p-type semiconductor oxide. Al_2O_3 is not a part of the ohmic contact (see column 3, lines 30-36).

In contrast thereto, claim 8 is directed to an ohmic contact that includes a mixture of p-type semiconductor oxide and metal. Claim 16 is directed to an ohmic contact that includes a layer of p-type semiconductor oxide and a conductive layer. Accordingly, it is respectfully submitted that Hartnagel et al. does not anticipate claims 8 and 16 and therefore, these claims are allowable.

With regard to the rejection in view of Nitta, it is respectfully submitted that Nitta does not disclose an ohmic contact including a mixture of p-type semiconductor oxide and metal. According to Nitta's disclosure, the electrode (105) formed on p-type InAlGaN may be metal (see column 2, lines 37-42, column 3, lines 41-45) or a compound of metal and oxygen such as ITO or SnO_2 (see column 4, lines 30-35) but not a mixture of metal and a compound of metal and oxygen. Furthermore, even if one were to allow that Nitta discloses an electrode that is made of metal and a compound of metal and oxygen, it is respectfully submitted that both ITO and SnO_2 are degenerate n–type semiconductors, which are quite different from a p-type semiconductor oxide as recited in claims 8 and 16.

Accordingly, it is respectfully submitted that Nitta does not anticipate claims 8 and 16 and therefore, these claims are allowable.

Finally, with regard to the rejection in view of Nakamura et al., it is respectfully submitted that the transparent contact used in Nakamura is metal but not a mixture of p-type semiconductor oxide and metal. The p-type electrode (15) is a layer of metallic material (see column 5, lines 40-41 and column 5, line 53-column 6, line 7). Moreover, the following described process of annealing the metal electrode (15) is performed in a non-oxidative or inner atmosphere to maintain its metallic characteristic. As to the protective film (411), the protective film 411 is electrically insulating (see column 10, lines 5-23). Therefore, it is not a part of the electrode or the contact.

Accordingly, it is respectfully submitted that Nakamura does not anticipate claims 8 and 16 and therefore, they are allowable.

Claims 9-15 and 17-27 depend, either directly or indirectly, on claims 8 and 16, respectively. Therefore, they are allowable for at least the reasons claim 8 and 16 are allowable. These claims further define and augment the features of Applicants' invention.

PATENT

CONCLUSION

In view of the foregoing, Applicants believe all claims now pending in this Application are in condition for allowance. The issuance of a formal Notice of Allowance at an early date is respectfully requested.

If the Examiner believes a telephone conference would expedite prosecution of this application, please telephone the undersigned at 415-576-0200.

Respectfully submitted,

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PATENT

Versions with Markings to Show Changes Made

1. A method for manufacturing ohmic contact to a semiconductor including the steps of: forming a plurality of metals on a semiconductor material; heat-treating the plurality of metals in an oxidizing environment so that at least one of the plurality of metals is oxidized to form a p-type semiconductor oxide.

2. A manufacturing method as claimed in claim 1 wherein the semiconductor material is p-type $Al_xGa_yIn_zN$, and $0<x,y,z<1$, and $x+y+z = 1$.

3. A manufacturing method as claimed in claim 1 wherein the plurality of metals includes at least a transition metal which can transform into a p-type semiconductor oxide.

4. A manufacturing method as claimed in claim 1 wherein the plurality of metals includes at least a noble metal which is one of Au, Pt, Rh, Ru, and Ir.

5. A manufacturing method as claimed in claim 1 wherein the film formed on the semiconductor material can be an alloy of transition metal and noble metal.

6. A manufacturing method as claimed in claim 2 wherein the semiconductor material is p-type GaN.

7. A manufacturing method as claimed in claim 3 wherein the transition metal is one of Ni, Mn, Fe, Co, Cr, Cu and Pd.

8. (Amended) An ohmic contact ~~to~~ in a semiconductor device which is formed on a semiconductor material, ~~including~~ the ohmic contact comprising a mixture of p-type semiconductor oxide and metal.

9. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a single oxide.

10. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a mixture of various oxides.

11. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a solid solution of various oxides.

12. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the semiconductor material is p-type $Al_xGa_yIn_zN$, and $0<x,y,z<1$, and $x+y+z = 1$.

13. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide is one of NiO, MnO, FeO, Fe_2O_3, CoO, CrO, Cr_2O_3, CrO_2, CuO, Cu_2O, SnO, Ag_2O, $CuAlO_2$, $SrCu_2O_2$ and PdO.

14. (Amended) ~~An~~ The ohmic contact as claimed in claim 8 wherein the metal is Au, Pt, Rh, Ru, or Ir.

15. (Amended) ~~An~~ The ohmic contact as claimed in claim 12 wherein the semiconductor material is p-type GaN.

16. (Amended) An ohmic contact ~~to~~ in a semiconductor device, which is formed on a semiconductor material, ~~including~~ the ohmic contact comprising a layer of p-type semiconductor oxide and a conductive layer.

17. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the semiconductor material is p-type $Al_xGa_yIn_zN$, and $0<x,y,z<1$, and $x+y+z = 1$.

18. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the p-type semiconductor oxide is one of NiO, MnO, FeO, Fe_2O_3, CoO, CrO, Cr_2O_3, CrO_2, CuO, Cu_2O, SnO, Ag_2O, $CuAlO_2$, $SrCu_2O_2$, $LaMnO_3$, $YBa_2Cu_4O_8$ and PdO.

19. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a single oxide layer.

20. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a plurality of layers of oxides of the same conductivity type.

21. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a mixture layer of various oxides.

22. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a solid solution layer consisting of various oxides.

23. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the conductive layer includes a single metal layer.

24. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the conductive layer includes a plurality of metal layers.

25. (Amended) ~~An~~ The ohmic contact as claimed in claim 16 wherein the conductive layer is a transparent conductive film.

26. (Amended) ~~An~~ The ohmic contact as claimed in claim 17 wherein the semiconductor material is p-type GaN.

27. (Amended) ~~An~~ The ohmic contact as claimed in claim 25 wherein the transparent conductive film is conductive oxide, including indium-tin oxide, ZnO and ZnO doped with Ga, In, Al or Ce.

6. A manufacturing method as claimed in claim 2 wherein the semiconductor material is p-type GaN.

7. A manufacturing method as claimed in claim 3 wherein the transition metal is one of Ni, Mn, Fe, Co, Cr, Cu and Pd.

8. An ohmic contact to a semiconductor which is formed on a semiconductor material, including a mixture of p-type semiconductor oxide and metal.

9. An ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a single oxide.

10. An ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a mixture of various oxides.

inherent

11. An ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide includes a solid solution of various oxides.

12. An ohmic contact as claimed in claim 8 wherein the semiconductor material is p-type $Al_xGa_yIn_zN$, and $0<x,y,z<1$, and $x+y+z = 1$.

13. An ohmic contact as claimed in claim 8 wherein the p-type semiconductor oxide is one of NiO, MnO, FeO, Fe_2O_3, CoO, CrO, Cr_2O_3, CrO_2,

CuO, Cu_2O, SnO, Ag_2O, $CuAlO_2$, $SrCu_2O_2$ and PdO.

14. An ohmic contact as claimed in claim 8 wherein the metal is Au, Pt, Rh, Ru, or Ir.

15. An ohmic contact as claimed in claim 12 wherein the semiconductor material is p-type GaN.

16. An ohmic contact to a semiconductor, which is formed on a semiconductor material, including a layer of p-type semiconductor oxide and a conductive layer.

17. An ohmic contact as claimed in claim 16 wherein the semiconductor material is p-type $Al_xGa_yIn_zN$, and $0<x,y,z<1$, and $x+y+z = 1$.

18. An ohmic contact as claimed in claim 16 wherein the p-type semiconductor oxide is one of NiO, MnO, FeO, Fe_2O_3, CoO, CrO, Cr_2O_3, CrO_2, CuO, Cu_2O, SnO, Ag_2O, $CuAlO_2$, $SrCu_2O_2$, $LaMnO_3$, $YBa_2Cu_4O_8$ and PdO.

19. An ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a single oxide layer.

20. An ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a plurality of layers of oxides of the

same conductivity type.

21. An ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a mixture layer of various oxides.

22. An ohmic contact as claimed in claim 16 wherein the layer of semiconductor oxide includes a solid solution layer consisting of
inherent
various oxides.

23. An ohmic contact as claimed in claim 16 wherein the conductive layer includes a single metal layer.

24. An ohmic contact as claimed in claim 16 wherein the conductive layer includes a plurality of metal layers.

25. An ohmic contact as claimed in claim 16 wherein the conductive layer is a transparent conductive film.

26. An ohmic contact as claimed in claim 17 wherein the semiconductor material is p-type GaN.

27. An ohmic contact as claimed in claim 25 wherein the transparent conductive film is conductive oxide, including indium-tin oxide, ZnO and ZnO doped with Ga, In, Al or Ce.

COMPARISON COPY

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SUBSTITUTE SPECIFICATION

OHMIC CONTACT TO SEMICONDUCTOR ~~DEVICES AND~~ DEVICES AND METHOD OF MANUFACTURING THE SAME

BACKGROUND OF THE INVENTION

Field of the invention

This invention relates to an ohmic contact ~~to~~for semiconductor devices and its manufacturing method, particularly an ohmic contact to p-type gallium nitride and the method of manufacturing the same.

Description of prior art

In recent years, gallium nitride (hereinafter referred to as GaN) has been broadly used in the fabrication of short-wavelength light-emitting diodes, laser diodes, photo-detectors and microelectronic components, etc. Good ohmic contact is especially important to commercialized light-emitting devices. Currently, the specific contact resistance for n-type GaN has been reduced to about 10^{-4}~—10^{-8} $\Omega\cdot cm^2$. As for p-type GaN, however, the specific contact resistance can only attain 10^{-2}~—10^{-3} $\Omega\cdot cm^2$, much higher than that for the contact to n-type GaN. Such a high interface resistance markedly affects the performance and reliability of these devices. Therefore, it is an important issue for the scientists and engineers to lower the specific contact resistance of the contact to p-type GaN. Until now, most conventional methods to manufacture contacts to p-type GaN

deposit the metals directly. For example, in ~~US~~U.S. patent ~~no.~~No. 5,652,434, the Nichia Chemical Industrial Company uses Ni or Ni/ Au in its light-emitting diodes (LED) to form a contact. In addition, in ~~US~~U.S. patent ~~no.~~No. 5,739,554, Cree Research Company uses Ti/Au, Ti/Ni or Ni/Au in its LED to form contact. But neither described the specific contact resistance of the contacts. In other references, other kinds of metals are disclosed, such as Au, Ni, Ti, Pd, Pt, W, WSi_x, Ni/Au, Pt/Au, Cr/Au, Pd/Au, Au/Mg/Au, Pd/Pt/Au, Ni/Cr/Au, Ni/Pt/Au, Pt/Ni/Au, Ni/Au-Zn, Ni/Mg/Ni/Si, etc. However, the specific contact resistance of the above metal contacts can only attain 10^{-2}~10^{-3} cm^{-2}, which is higher than 10^{-4} cm^{-2} generally required for optoelectronic devices. In addition, almost all of the above metals do not exhibit ohmic behavior.

SUMMARY OF THE INVENTION

Accordingly, the object of this invention is to provide an ohmic contact to semiconductor devices and its manufacturing method by which the interface resistance of ohmic contact is lowered so as to improve the performance and reliability of semiconductor devices.

This invention provides a new semiconductor manufacturing process which can form an ohmic contact to p-type GaN with a low interface resistance for application in the fabrication of GaN-based devices. The manufacturing method of this invention forms a film, which includes transition metal and noble metal, on the semiconductor substrate. Then, the film is heat-treated and oxidized to obtain an ohmic contact with a low specific contact resistance. So formed, an ohmic contact can meet the requirement of an optoelectronic device; that is, the specific contact resistance of the ohmic contact is lower than 10^{-4} cm^{-2}.

BRIEF DESCRIPTION OF THE DRAWINGS

The following detailed description, given by way of example and not intended to limit the invention solely to the embodiments described herein, will best be understood in conjunction with the accompanying drawings in which:

Fig. 1 is a diagram illustrating the structure of an ohmic contact according to one embodiment of the invention;

Fig. 2 is a diagram illustrating the structure of an ohmic contact according to another embodiment of the invention;

Fig. 3a is a diagram illustrating a pattern formed on a substrate in the CTLM measurement used in this invention;

Fig. 3b illustrates the current-voltage (I-V) measurement of Ni-Au contacts formed on p-type GaN and heat-treated in various ~~ambiences,~~ambiances; and

Fig. 4 shows the specific contact resistance obtained by oxidizing Ni/Au layers of different thickness.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The method of fabricating an ohmic contact to semiconductors according to this invention includes the steps of: coating a transition metal and a noble metal or an alloy thereof on a semiconductor material, then ~~heat-~~heat-treating the metal layer in an oxidizing ambience so that the transition metal is oxidized to form an oxide.

The semiconductor described above is p-type GaN. The transition metal can be Ni, Mn, Cr, Cu, Fe, Co or Pd, etc. The noble metal can be Au, Pt, Rh, Ru, or Ir, etc.

The oxide mentioned above is a single oxide, or a mixture of various oxides such as NiO/CoO or a solid solution of various oxides such as ~~$Ni_xCo_{1-x}O(0<x<1)$ etc.,~~ $Ni_xCo_{1-x}O(0<x<1)$,

etc. The metal in the above film can be a single metal, or various metals or an alloy thereof.

Another layer of metal can be further formed thereon. Such layer of metal can a single metal such as Au or Ni, a plurality of layers of metals, or a layer of alloy such as Cr/Au or Ti/Pt/Au, etc., for connecting with other circuits.

The ohmic contact formed by the above method has different structures according to different preparation methods of the transition metal and the noble metal. In the first embodiment, after heat-treatment, the transition metal and the noble metal formed on the semiconductor material 10 become~~s~~ a mixture of semiconductor oxide 12 and metal 14 as shown in Fig. 1.

In the first embodiment, the above semiconductor material 10 is formed on a sapphire substrate, with an undoped GaN layer and a GaN layer doped with Mg, each 2 μm thick, formed by MOCVD method. Using this semiconductor material as a test sheet, it is heat-treated in a nitrogen atmosphere to make the Mg doped GaN layer become p-type. This test sheet has an electron concentration of 1×10^{17} cm^{-3} for its undoped GaN layer and a hole concentration of 2×10^{17} cm^{-3} for its p-type GaN. A CTLM (circular transmission line model) method is used in the invention to calculate the specific contact resistance (ρ_c).

Next, the fabrication and measurement procedure for the ohmic contact of this invention is described, which includes the steps of: ~~(i) forming~~(i) forming a photoresist layer on the GaN 20 with a CTLM pattern; ~~(ii) removing~~(ii) removing the GaN surface oxide by dipping the test sheet in a solution of $HCl:H_2O$= 1: 1 for 3 minutes, then blowing dry the GaN and putting the test sheet immediately into a vacuum chamber of an electron-gun coating system; ~~(iii)~~ (iii) degassing the chamber of the electron-gun coating system to a high vacuum, then proceeding with the coating of various metals; ~~(iv) lifting off~~(iv) lifting off a part of metal film to form a metal

pattern 22 as shown in Fig. 3(a); ~~(v)~~ (v) heat-treating the test sheet in air, oxygen, 10% H_2- 90% N_2 or nitrogen atmosphere, in which the temperature is from 200°C to 900°C, and the time is 10 minutes; ~~(vi) conducting I-V~~(vi) conducting I-V measurement for the test sheet; and ~~(vii) analyzing~~(vii) analyzing the ρ_c values.

Next, the CTLM measurement and analysis used in the above steps is described, in which the measurement of I-V characteristic~~to~~ respectively is used to figure out the resistance between the metals within the inner ring and outside the outer ring of two concentric circles. The analysis of ρ_c is conducted on the I-V curves of ±0.5 V and ±20 mV. Generally speaking, the contact structure~~s~~ of this invention exhibits ohmic behavior within the above testing range, i.e., it is provided with a linear I-–V curve. Therefore, the specific contact resistance can be calculated through the slope of the curve. The formula of calculating ρ_c for the CTLM method is as follows:

$$R_t = (R_{sh}/2\pi)\,[\ln(R/r) + L_t(r^{-1}+R^{-1})]$$

$$\rho_c = R_{sh} \times L_t^2$$

where R_t serves as the total resistance of the I-–V measurement, R_{sh} is the sheet resistance, ~~and~~ r and R respectively represent the radius of the inner and outer concentric circles, and L_t is the transfer length. According to the above formula, a diagram can be formed through R_t of the ~~I-V~~I-V measurement to the ln(R/r). Then a linear curve can be obtained by processing the diagram with the least square linear curve fitting method. The slope of the obtained curve is $R_{sh}/2\pi$. The intercept can thus be calculated by the formula when R equals to r, to be $R_{sh}L_t/r\pi$, so that R_{sh} and L_t can be figured out to further calculate ρ_c.

Fig. 3b illustrates the measurement results of this invention, which shows the I-–V characteristic of Ni/Au

contacts formed on p-type GaN and heat-treated in various atmospheres, wherein curve A represents the situation in which Ni/Au is heat-treated in air or oxygen atmosphere, curve B, in nitrogen atmosphere, and curve C, in 10% H_2-90% N_2 atmosphere. The temperature of the heat treatment process is 500~~–~~°C and the heat-treating time is 10 minutes. The slope of the curve is a maximum, that is, the ρ_c value is a minimum, and the positive current and the negative current ~~is~~are symmetrical to the original point after oxidizing the Ni/Au film. On the other hand, the Ni/Au layer is still a metal film after the test sheet is heat-treated in nitrogen or 10% H_2-90% N_2. This results in an increase in the obtained ρ_c. The I-V curve does not maintain linearity when the metal contact is biased at a higher voltage, and the positive and negative currents are not symmetrical to each other. Please also refer to the following Table 1, in which the Ni/Au thin film heat-treated in air of this embodiment still displays a good conductivity.

Table 1

Condition	Sheet resistance(Ω/□)	Resistivity(μΩ·cm)
As- deposited	11.87	17.8
N_2, 500°C, 10 min	16.82	25.2
Air, 500°C, 10 min	38.94	97.4

Fig. 4 shows the specific contact resistance of the contacts formed by oxidizing Ni/Au layers of various thicknesses on the p-type GaN, wherein~~,~~ curve A' represents that Ni is 50 nm and Au is 125 nm, curve B' represents that Ni is 10 nm and Au is 25 nm, and curve C' represents that Ni is 10 nm and Au is 5 nm. The oxidation of the above process is heating the test sheet in air for 10 minutes. According to the current experimental data, the minimum specific contact resistance is $1.0\times10^{-4}\ \Omega\cdot cm^2$.

Using X-ray diffraction to analyze the Ni(10 nm)/Au(5 nm) films heat-treated at 500°C for 10 minutes, the result shows that Ni converts to NiO and Au is still metallic after being heat-treated in air. On the contrary, when the test sheet is heat-treated in nitrogen or 10% H_2-90% N_2, the Ni/Au film is still metallic, but the ρ_c value is about 10^{-1} to 10^{-2} $\Omega\cdot cm^2$. Furthermore, if instead of the above Ni(10 nm)/Au(5 nm), a 50 nm thick Ni film is coated on the p-type GaN and then the same oxidation process is performed to form NiO, and the specific contact resistance of the NiO contact to p-type GaN is measured to analyze the effect of NiO, the ρ_c value is only about 0.1 $\Omega\cdot cm^2$, but its I-V curve is a linear curve over a wide range. This means that an ohmic contact is formed between NiO and p-GaN. However, the ρ_c value is high since the NiO thus formed is highly resistant. This indicates that the existence of NiO causes the oxidized Ni/Au film form an ohmic contact. Au primarily gives the thin film~~with~~ an excellent conductivity, because Au can—not form an excellent ohmic contact to p-type GaN. According to the prior art, it has been reported that ρ_c is only 53 $\Omega\cdot cm^2$ (L. L. Smith, et al., J. Mater. Res. 12, ~~2249(1997))~~2249 (1997)) and 2.6×10^{-2} $\Omega\cdot cm^2$ (T. Mori et al., Appl. Phys. Lett. 69, 3537~~(~~ (1996)) for Au contacts. It has also been reported that stoichiometric NiO is insulating, but becomes p-type if doping with Li^+ or creating Ni^{3+} ion vacancies in the NiO. Doping NiO with Li_2O can reduce its resistivity to 0.1 $\Omega\cdot cm$ (Z. M. Jarzebski, Oxide Semiconductors (Pergamon press, Oxford, 1973), Chap. 10). Ni^{2+} ion vacancies formed during the oxidization of Ni create holes (N. Birks and G. H. Meier, Introduction to High Temperature Oxidation of Metals (Edward Arnold, London, 1983), Chap. 4). Therefore, it is inferred that NiO formed in the oxidized Ni/Au is a p-type semiconductor. Au and P-type NiO, which are in a condition of mixed morphology, have a low interface

resistance with P-type GaN and can form an ohmic contact to P-type GaN. Hence, Ni/Au film can form an ohmic contact to p-type GaN after oxidation and heat-treatment, and is provided with a low specific contact resistance.

According to the above inference, any thin film including p-type semiconductor oxide and Au can form an excellent ohmic contact with p-type GaN. In addition to NiO, many oxides can be used to form a p-type semiconductor such as MnO, FeO, Fe_2O_3, CoO (Z. M. Jarzebski, Oxide ~~Semiconducotrs~~Semiconductors (Pergamon press, Oxford, 1973), Chap. 11), ~~PdO(R.~~PdO (R. Uriu et al., J. Phys. Soc. Jpn 60, 2479 (1991)), ~~$CuAlO_2$(H.~~$CuAlO_2$ (H. Kawazoe et al., Nature 389, ~~939(1997)), $SrCu_2O_2$(A.~~939 (1997)), $SrCu_2O_2$ (A. Kudo et al., Appl. Phys. Lett. 73, ~~220(1998)), Rh_2O_3(A.~~220 (1998)), Rh_2O_3 (A. Roy and J. Ghose, Mater. Res. Bull 33, 547_(1998)), CrO, Cr_2O_3, CrO_2, CuO, Cu_2O, SnO, Ag_2O, $LaMnO_3$, or $YBa_2Cu_4O_8$, etc.; therefore, it is also possible to form an ohmic contact to p-type GaN using a mixture of this kind of oxide and Au. Furthermore, Au can be replaced by other metals if the metal does not oxidize after heat-treatment. Normally, any noble metal can be used, for example~~,~~ Au, Pt, Rh, Ru, and Ir, etc.

Referring to Fig. 2, since the interface impedance of the p-type semiconductor oxide and p-type GaN is very low, and the metal can form an ohmic contact having a low resistivity with the p-type semiconductor oxide, another embodiment of this invention comprises sequentially forming a layer of p-type semiconductor oxide 12 and a layer of metal 24 on the p-type GaN 10 to form an ohmic contact to p-type GaN, such as p-GaN/p-NiO/Cr/Au, etc.

In the above embodiments, the ohmic contact to p-type GaN is described. However, the method of fabricating an ohmic contact can be applied in practice to p-type $Al_xGa_yIn_zN$ material, where $0<x,y,z<1$, and $x+ y+ z = 1$.

In the past, the specific contact resistance of a contact formed on p-type GaN could attain only 10^{-2}~10^{-3} $\Omega\cdot cm^2$, but the ohmic contact of this invention can obtain a much lower interface resistivity of 1.0×10^{-4} $\Omega\cdot cm^2$. This improvement has been applied to the fabrication of LEDs and ~~GaN-based~~GaN-based laser diodes with good performance.

Furthermore, the metal formed on the semiconductor material in the last embodiment can be replaced by a transparent conductive film, such as indium-tin oxide(ITO), ZnO or ZnO doped with Ga, In, Al or Ce, etc.

While the present invention has been particularly shown and described with reference to a preferred embodiment, it will be readily appreciated by those of ordinary skill in the art that various changes and modifications may be made without departing from the spirit and scope of the invention. It is intended that the claims be interpreted to cover the disclosed embodiment, those alternatives which have been discussed above and all equivalents thereto.

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